

Singlet Boson in Supersymmetric Model as a Mimic of the Standard Model Higgs at the LHC

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Abstract

We show that a gauge singlet scalar boson in low-energy supersymmetric model may behave as the standard model (SM) Higgs boson if the singlet couples to (heavy) vector-like colored particles. In this case, the SM-Higgs-like signal at the LHC can be mimicked by the singlet production process for wide range of the singlet mass.

In the field of particle physics, Higgs boson is the most important particle which should be experimentally found. Discovery of the Higgs boson itself is of course a great progress because it confirms the Higgs mechanism as the origin of electroweak symmetry breaking. Once discovered, in addition, we will also be able to acquire information about the physics beyond the standard model (SM) by detailed study of the Higgs boson. This is because the properties of Higgs, in particular the Higgs mass, are strongly dependent on how the SM is embedded into the new physics model.

The most prominent example of physics beyond the SM is the low-energy supersymmetry (SUSY); the minimal SUSY SM (MSSM) predicts the existence of “light” Higgs boson. At the tree level, the MSSM predicts the Higgs mass to be smaller than the Z -boson mass. Even if loop corrections are taken into account, the upper bound on the Higgs mass is ~ 135 GeV assuming that the stop mass is lighter than ~ 2 TeV [1]. In many extended SUSY models, there still exists light Higgs boson. For example, in the next-to-the MSSM (NMSSM), which is the model with gauge-singlet superfield, the lightest Higgs mass is predicted to be smaller than 140 GeV as far as the perturbativity of coupling constants up to the grand unified theory (GUT) scale is assumed [2]. Thus, the existence of the light Higgs boson is a crucial check point of low-energy SUSY.

The LHC experiment is about to discover the Higgs boson if its mass is within the accessible range. Even if a Higgs-like object is found, however, it would be still a question whether it is really the Higgs boson which is responsible for the electroweak symmetry breaking. In the study of low-energy SUSY, this is an important question because some class of SUSY models may be discriminated based on the properties of the observe Higgs-like object. Thus we should clarify if there is any possibility of a particle which may mimic SM-Higgs-like signals at the LHC.

In non-SUSY case, there are such possibilities [3, 4]. In particular, the Higgs-like signal may show up at the LHC if there exists a singlet boson s which couples to vector-like colored fermions (or directly couples to gluon via the dimension 5 interaction of $sG_{\mu\nu}G_{\mu\nu}$, with $G_{\mu\nu}$ being the field strength of the gluon field) [4]. Because a singlet chiral multiplet appears in various SUSY models, including the NMSSM, we pursue this possibility in the framework of SUSY model .

In this letter, we will show that the SM-Higgs-like signal at the LHC can be easily mimicked if there exists a singlet field which couples to a new vector-like colored chiral supermultiplets. Thus, even if the LHC experiment finds a SM-Higgs-like signal at the mass

region above the SUSY Higgs mass bound, low-energy SUSY is still a possibility. For this mechanism to work, we also show that there should exist colored particles with their masses smaller than $500 - 600$ GeV.

First let us briefly summarize the basic idea how the SM-Higgs-like signal is mimicked in the SUSY model with singlet. As is well-known, the most efficient process of producing Higgs boson at the LHC is the gluon fusion process, which is induced by the top-loop diagram. Thus, if the singlet field couples to colored particles, then we expect a significant production cross section for the singlet field due to the gluon fusion. In addition, in SUSY models with singlet (as in the case of NMSSM), the singlet mixes with the SM-like Higgs boson due to the superpotential and SUSY breaking interactions. Consequently, if the singlet dominantly decays via the mixing, then the LHC signal of the singlet production is like that of the SM-Higgs production.

To see this can really happen in SUSY model, we adopt the simplest set up. We introduce the gauge-singlet superfield S as well as the following vector-like chiral multiplets: D_i ($\mathbf{3}, \mathbf{1}, -\frac{1}{3}$), \bar{D}_i ($\bar{\mathbf{3}}, \mathbf{1}, \frac{1}{3}$), L_i ($\mathbf{1}, \mathbf{2}, -\frac{1}{2}$), and \bar{L}_i ($\mathbf{1}, \bar{\mathbf{2}}, \frac{1}{2}$), where the representations for the SM gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$ are shown in the parenthesis. Because GUT is one of the strong motivation to consider SUSY, we have introduced L and \bar{L} so that the newly introduced fields can be embedded into the complete multiplet of $SU(5)_{\text{GUT}}$. As we will show below, L and \bar{L} are not important for the enhancement of the singlet-boson production at the LHC. In our analysis, we introduce $N_{\mathbf{5}}$ -pairs of vector-like multiplets; the index i runs from 1 to $N_{\mathbf{5}}$. Notice that the perturbativity of the gauge coupling constant breaks down at high-energy scale if $N_{\mathbf{5}}$ is too large. Requiring the perturbativity up to the GUT scale, we require $N_{\mathbf{5}} \leq 4$ in our analysis.

Motivated by the NMSSM, we adopt the following form of the superpotential for the singlet field:

$$W \supset \lambda S H_u H_d + \frac{1}{3} \kappa S^3 + y_D S \bar{D}_i D_i + y_L S \bar{L}_i L_i, \quad (1)$$

where H_d and H_u are down- and up-type Higgses, respectively. For simplicity, the Yukawa coupling constants for the $S \bar{D}_i D_i$ and $S \bar{L}_i L_i$ terms are taken to be i -independent; this may be due to $SU(N_{\mathbf{5}})$ flavor symmetry. We have checked that our conclusion does not significantly change even if we do not adopt this assumption. In addition, the relevant part of the soft-SUSY breaking term is given by

$$\mathcal{L}_{\text{soft}} \supset -m_{H_d}^2 |H_d|^2 - m_{H_u}^2 |H_u|^2 - m_S^2 |S|^2 - \left(\lambda A_\lambda S H_u H_d + \frac{1}{3} \kappa A_\kappa S^3 + \text{h.c.} \right). \quad (2)$$

In our analysis, for simplicity, we fix some of the parameters as

$$A_\lambda = 500 \text{ GeV}, \quad A_\kappa = -100 \text{ GeV}. \quad (3)$$

The Higgs potential is also sensitive to some of the parameters in the MSSM Lagrangian. Here, we take one of the important parameter, the tri-linear coupling for the stop (normalized by the top Yukawa coupling constant), as $A_t = 2 \text{ TeV}$, while other tri-linear scalar coupling parameters in the MSSM sector are taken to be 0. Here, we have adopted a relatively large value of the A_t -parameter in order to satisfy the LEP bound for the lightest Higgs boson mass[8]. Furthermore, the masses of all the MSSM sfermions are taken to be 1 TeV.^{#1}

Then, with other parameters being properly chosen, Higgs bosons acquire vacuum expectation values; rest of the parameters (i.e., λ , κ , $m_{H_d}^2$, $m_{H_u}^2$, m_S^2) are determined by fixing the following quantities:

$$m_Z, \quad \tan \beta = \langle H_u \rangle / \langle H_d \rangle, \quad v_s = \langle S \rangle, \quad \mu_{\text{eff}} = \lambda v_s, \quad m_{h_2},$$

where $\langle \dots \rangle$ denotes vacuum expectation value. Here, μ_{eff} plays the role of SUSY invariant Higgs mass (so-called μ -parameter) in the MSSM. In addition, once the singlet field gets a vacuum expectation value, then the newly introduced vector multiplets also become massive.^{#2}

In the present model, the Higgs bosons are composed of five neutral and two charged scalar bosons: three CP-even Higgs bosons h_a (with $m_{h_1} < m_{h_2} < m_{h_3}$), two CP-odd Higgs bosons and charged Higgs bosons.^{#3} Because we are interested in the SM-Higgs-like signal at the LHC, we concentrate on the CP-even Higgs sector in the following.

The mass eigenstates h_a are related to the gauge eigenstates using the unitary matrix S_{aA} as follows:

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = \begin{pmatrix} S_{1d} & S_{1u} & S_{1s} \\ S_{2d} & S_{2u} & S_{2s} \\ S_{3d} & S_{3u} & S_{3s} \end{pmatrix} \begin{pmatrix} h_d^0 \\ h_u^0 \\ s \end{pmatrix}, \quad (4)$$

where h_d^0 , h_u^0 , and s are the real scalars in the gauge eigenstates H_d , H_u , and S , respectively. In the following, we consider the case that h_2 is (almost) the singlet field, so that $|S_{2s}| \gg |S_{1s}|$, $|S_{3s}|$, $|S_{2d}|$, $|S_{2u}|$.

^{#1}We assume that the gauginos are so heavy that they do not affect the following analysis.

^{#2}One may also introduce a bare mass term for the vector-like multiplets. Extension of our analysis to such a case is straightforward.

^{#3}We assume that the CP violation in the Higgs sector is negligible so that there is no mixing between the CP-even and CP-odd sectors.

Now, we are at the position to discuss production and decay processes of the singlet Higgs at the LHC. The gluon fusion cross section for the process $pp \rightarrow h_2 \rightarrow F$ (with F denoting the final state of the decay of h_2) is given by

$$\sigma(pp \rightarrow h_2 \rightarrow F) = \frac{\Gamma(h_2 \rightarrow F)}{\Gamma_{\text{total}}} \sigma(pp \rightarrow h_2), \quad (5)$$

with

$$\sigma(pp \rightarrow h_2) = \Gamma(h_2 \rightarrow gg) \frac{\pi^2}{8m_{h_2}s} \int_0^1 dx_1 \int_0^1 dx_2 \delta(x_1 x_2 - m_{h_2}^2/s) g(x_1) g(x_2), \quad (6)$$

where $\Gamma(h_2 \rightarrow F)$, $\Gamma(h_2 \rightarrow gg)$ and Γ_{total} are the partial decay widths of the decay processes $h_2 \rightarrow F$, $h_2 \rightarrow gg$ and the total decay width of h_2 , respectively. In Eq.(6), \sqrt{s} is the center of mass energy and $g(x)$ is the gluon distribution in the proton. In the present set up, the process $h_2 \rightarrow F$ may be induced by the mixing with H_d and H_u as well as by the loop diagrams with D_i and \bar{D}_i inside the loop.

With a relevant choice of parameters, we found that the process $h_2 \rightarrow gg$ is dominated by the loop diagrams with D_i and \bar{D}_i inside the loop, while the decay processes into the weak boson pairs $h_2 \rightarrow VV$ (with $VV = ZZ$ or W^+W^-) are due to the mixing effect. Thus,

$$\Gamma(h_2 \rightarrow gg) \simeq |S_{2s}|^2 \frac{m_{h_2}^3 \alpha_s^2}{144\pi^3 v_s^2} |N_5 I_D|^2, \quad (7)$$

and

$$\Gamma(h_2 \rightarrow VV) \simeq |S_{2d} \cos \beta + S_{2u} \sin \beta|^2 \Gamma(h_{\text{SM}} \rightarrow VV), \quad (8)$$

where $\Gamma(h_{\text{SM}} \rightarrow VV)$ is the partial decay width of the SM Higgs boson (with the mass of m_{h_2}). In Eq.(7),

$$I_D = 3 [2x_D + x_D(4x_D - 1)f(x_D)], \quad (9)$$

where

$$f(x) = \begin{cases} -2 \arcsin^2(1/2\sqrt{x}) & \text{for } x > 1/4 \\ \frac{1}{2} \left[\ln \left(\frac{1 + \sqrt{1-4x}}{1 - \sqrt{1-4x}} \right) - i\pi \right]^2 & \text{for } x < 1/4 \end{cases}, \quad (10)$$

and $x_D = m_D^2/m_{h_2}^2 = y_D^2 v_s^2/m_{h_2}^2$ [5]. In fact, $I_D \simeq 1$ when $x_D \gtrsim 1$, so we approximate $I_D = 1$ in our numerical calculation. Then the results are insensitive to the choice of y_D (as far as m_D is assumed to be larger than m_{h_2}).

One important point is that the decay width $\Gamma(h_2 \rightarrow gg)$ (and hence the gluon fusion cross section) is proportional to $N_{\mathbf{5}}^2$; this is because the amplitude is proportional to the number of particles inside the loop. Thus, as we increase the number of vector-like chiral multiplets, the signal of singlet Higgs production process is enhanced.

Using the formulae given above as well as the numerical package NMSSMtools [6], we calculate the cross sections for the Higgs production processes in the present set up. We have calculated the decay width of the SM Higgs to gluon-gluon mode at the leading order. Decay widths of the SM Higgs (except for the gg mode) are calculated by HDECAY package [7].

First, we show the cross section for the process $pp \rightarrow h_2 \rightarrow VV$ normalized by the corresponding SM process:

$$R_{VV} \equiv \frac{\sigma(pp \rightarrow h_2 \rightarrow VV)}{\sigma(pp \rightarrow h_{\text{SM}} \rightarrow VV)}. \quad (11)$$

In our analysis, only the gluon fusion process, which is the dominant Higgs production process at the LHC, is taken into account.

In Figs. 1 and 2, we show the contours of constant R_{ZZ} for $\sqrt{s} = 7\text{TeV}$; we have checked that the behavior of $R_{W^+W^-}$ is almost identical. In the calculation, we have taken $\tan\beta = 3$ and $\mu_{\text{eff}} = 250\text{ GeV}$ (Fig. 1) and $\tan\beta = 5$ and $\mu_{\text{eff}} = 110\text{ GeV}$ (Fig. 2). In Fig. 1, the region with $m_{h_2} \lesssim 195\text{ GeV}$ is excluded because the lightest Higgs becomes lighter than the LEP bound (i.e., 114.4 GeV) [8]. Such a result is partly because the choice of $\tan\beta$ parameter. Indeed, if we adopt a slightly larger value of $\tan\beta$, the region with $m_{h_2} \lesssim 195\text{ GeV}$ becomes allowed. (See Fig. 2.) In the case of Fig. 2, R_{VV} is suppressed for $m_{h_2} \gtrsim 220\text{ GeV}$; in such a region, the decay mode of h_2 into Higgsino-like fermions becomes kinematically open.

In both figures, one can see that $R_{VV} \gtrsim 1$ can be realized in large fraction of the parameter space. Thus, the singlet production process may mimic the SM-Higgs production at the LHC. Notice that the masses of colored fermions are given by $m_D = y_D v_s$ and hence, assuming the perturbativity of the Yukawa coupling constant, the colored fermions are expected to be lighter than $\sim v_s$. Thus, for our scenario to work, there should exist colored fermions with masses of $O(100\text{ GeV})$. The detailed upper bound on the colored fermion masses depends on various parameters; for the case of Fig. 1, for example, $R_{VV} = 1$ requires $m_D \lesssim 630\text{ GeV}$ and 500 GeV for $m_{h_2} = 200\text{ GeV}$ and $m_{h_2} = 250\text{ GeV}$, respectively. Thus the search for the colored fermions should give a crucial test of the present scenario. The experimental signal of the production of such colored particles depends how they decay. In the present set up, D and \bar{D} may slightly mix with down-type quarks via Yukawa-type interactions. In such a

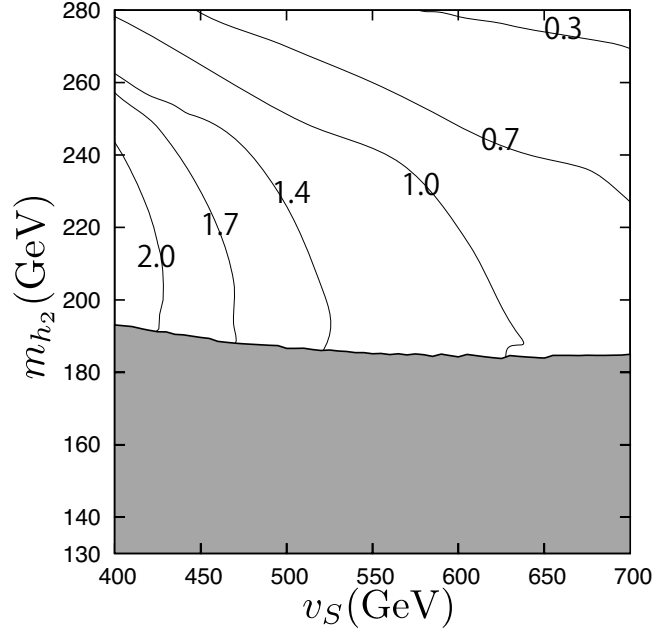


Figure 1: The contours of constant R_{ZZ} on v_s vs. m_{h_2} plane for $\sqrt{s} = 7\text{TeV}$. Here, we take $N_5 = 4$, $\tan\beta = 3$ and $\mu_{\text{eff}} = 250$ GeV. In the shaded region, the lightest Higgs boson mass is less than 114.4 GeV

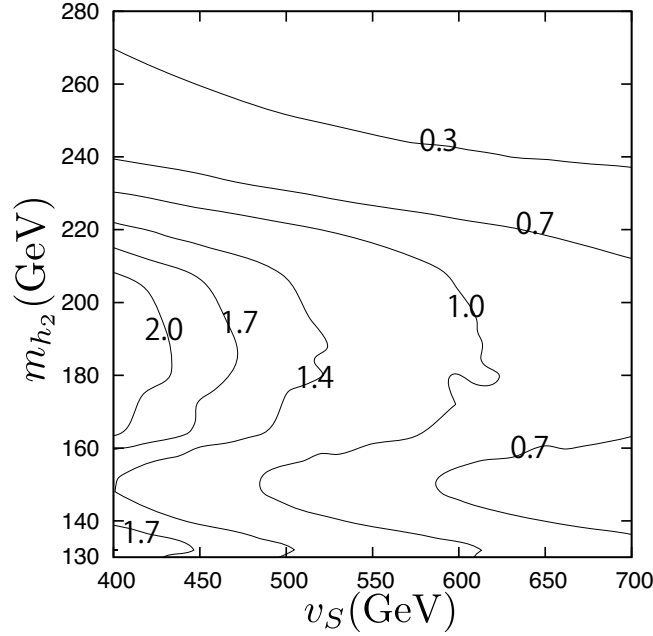


Figure 2: The contours of constant R_{ZZ} on v_s vs. m_{h_2} plane for $\sqrt{s} = 7\text{TeV}$. Here, we take $N_5 = 4$, $\tan\beta = 5$ and $\mu_{\text{eff}} = 110$ GeV.

case, they decay into an up-type light quark and W^\pm -boson. The current lower bound on the masses of such particles is about 400 GeV for $N_5 = 4$ [9].

Because the lightest Higgs mass is also an important parameter, we have calculated m_{h_1} in both cases. The results are shown in Figs. 3 and 4.

Finally, let us comment on the decay mode $h_2 \rightarrow \gamma\gamma$. As in the case of the process $h_2 \rightarrow gg$, the decay width for the process $h_2 \rightarrow \gamma\gamma$ may be also affected by the loop diagrams with the vector-like fermions inside the loop. Importantly, for $h_2 \rightarrow \gamma\gamma$, the W^\pm -loop diagram contribution is numerically significant as in the case of SM Higgs boson. Even though such a contribution is suppressed by the mixing factor $(S_{2d} \cos \beta + S_{2u} \sin \beta)$, we have checked that the effect of W^\pm -loop diagram is comparable to that of vector-like-fermion loop in the parameter region we have studied. Thus, the branching ratio $Br(h_2 \rightarrow \gamma\gamma)$ may significantly deviate from that of the SM Higgs boson.

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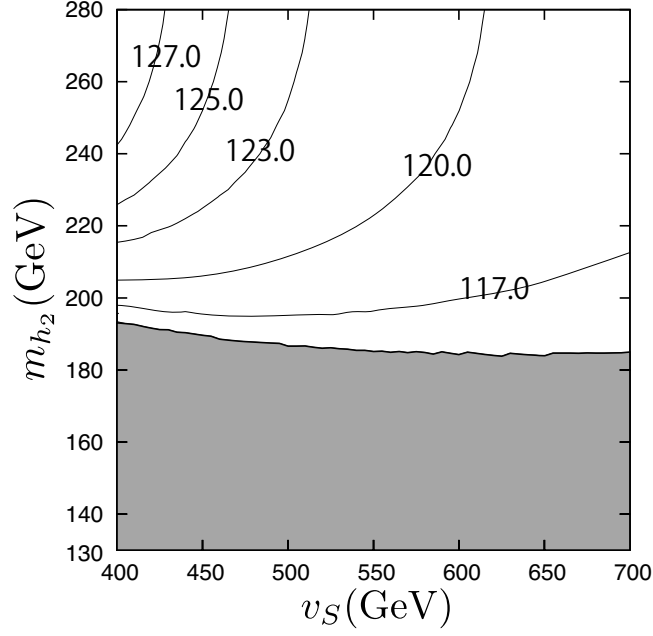


Figure 3: The contours of constant lightest Higgs mass on v_s vs. m_{h_2} plane. Here, we take $N_{\mathbf{5}} = 4$, $\tan \beta = 3$ and $\mu_{\text{eff}} = 250$ GeV. In the shaded region, the lightest Higgs boson mass is less than 114.4 GeV.

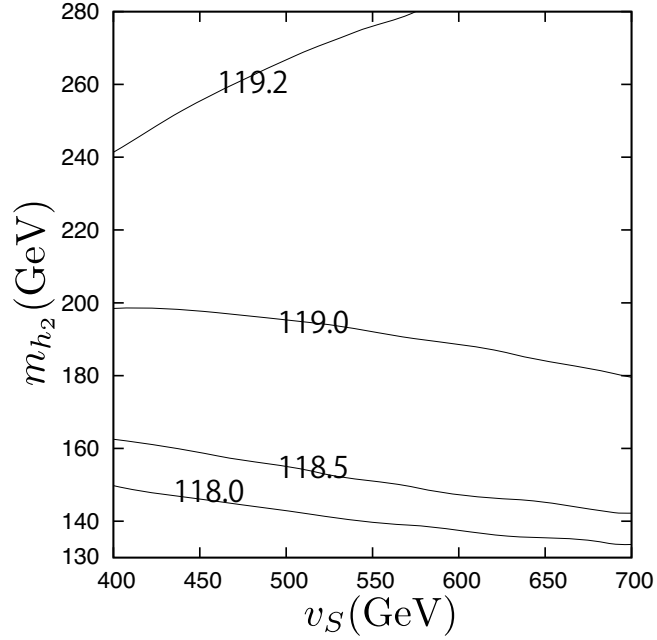


Figure 4: The contours of constant lightest Higgs mass on v_s vs. m_{h_2} plane. Here, we take $N_{\mathbf{5}} = 4$, $\tan \beta = 5$ and $\mu_{\text{eff}} = 110$ GeV.

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